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GLOBAL ENERGY AND ELECTRICITY FUTURES†

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Abstract -- By the middle of the next century, global energy demand, driven by population and economic growth, will be in the range of 2-4 times the present level, depending on the effectiveness of energy efficiency and conservation globally. Even with maximum realistic conservation, the electricity component will be more than 4 times present usage. A massive expansion of non-fossil sources would be needed to slow the future annual increase in carbon dioxide emissions to the atmosphere. At best, the contribution of the environmental trinity, solar, wind, and biomass, is not likely to exceed one-third of the electricity supply due to practical limitations. The bulk of the electricity will necessarily come from fossil fuels and from non-fossil sources such as hydro, nuclear, and geothermal energy . The annual carbon dioxide emissions will undoubtedly increase for the foreseeable future, even with intensive global conservation and efficiency efforts, unless the present constraints on a major expansion of these non-fossil sources are moderated.

INTRODUCTION

In our common role as trustees of the future, I base a projection of a next century global energy mix on past and present energy experience. To set the stage for this relatively near-term projection, I would like to imagine a scenario of the global energy situation a millennium hence. A scenario is like a novel whose outcome is the author's creation. Nevertheless, I will try to be practical.

A thousand years ago, the global population was about 300 million, 20 times less than today. A century ago, global population growth had a doubling time of 100 years, it is now about 75 years, and may be shorter in the coming century. Even an unrestrained doubling time of 200 years would mean a 2^5 or 32 times increase by the year 3000. Obviously this is ridiculous, and some stabilization will be enforced by Malthusian limits, so I have assumed that by the year 3000 the world's population might be only 4 times the present, and the average per capita energy end-use might be the same as in the U.S. today or 5 times the present global average, with a resultant annual global demand about 20 times today's. By that

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time, all fossil fuels would be very scarce, biomass and hydro would be at their practical limits providing perhaps 5% of the demand, the other renewables, solar, wind, etc., although very expensive because of the cost of energy storage, might provide about 20%, and the principal wide-spread large-scale energy source would be nuclear power (fission or fusion). Of course, in a thousand years some new source may be discovered, or "hot-rocks" from the earth's mantle may be tapped, or solar space mirrors may focus on earth receivers, or a new compact energy storage may make solar energy more important. However, in the last thousand years the only new source discovered was nuclear power. The point of this scenario is the need to maintain a flexible participating role for every energy option in our long-range planning. There are no single-choice solutions.

Now let us return to the relatively easy task of projecting to the next century. The economic growth that has provided the means for society's improvements has required a corresponding increase in energy supply. Energy has been the essential input to economic growth everywhere. During the recent decades, many thoughtful people have questioned whether the by-product effluents of such increasing energy use might produce seriously damaging and costly environmental consequences. Our concerns have expanded from smog to acid rain to global climate greenhouse issues. In each case, the root cause is energy use, and so a projection of future energy use may have particular relevance to these concerns. We face the very basic issue of finding an optimal balance between economic growth, related energy use, and the environment. I should emphasize that this must not be an irreconcilable conflict, as we obviously need all three. With this in mind, my colleague M. Searl and I have been studying the trend of the world's energy demand; how it might be managed by conservation and alternative energy sources; and what the resultant carbon emissions might be.

PREMISES

I will start by briefly describing the premises for our projections. It is generally recognized that energy and electricity use are historically intertwined with economic and population growth, and will become more so as we move from subsistence farming to the industrial-urban-farm patterns needed to support a large population. We have determined the recent trends in each of these, and projected them to the future with reasonable adjustments. Figure 1 shows the

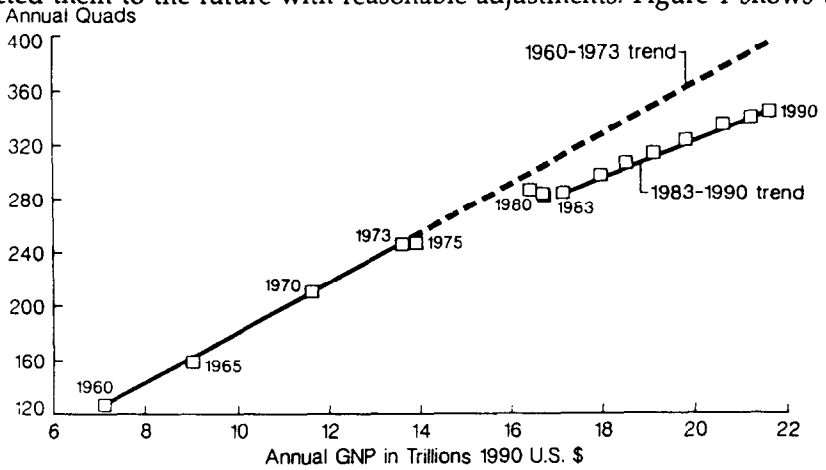

Fig. 1. World annual energy use in quads vs GNP (1960-1990)

world's total energy use vs its economic output. Figure 2 shows the world's electricity use vs it economic output. Figure 3 shows the direct (non-electric) use. It is important to note that the chaotic energy supply decade of 1973-83 merely shifted the relationship in total energy, and did not disturb the electricity/GNP tie.

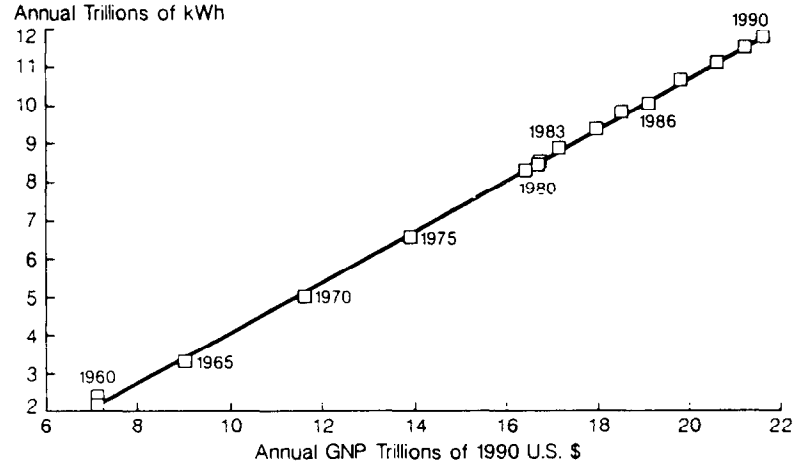

Fig. 2. World annual energy use in trillions of kWh vs GNP (1960-1990).

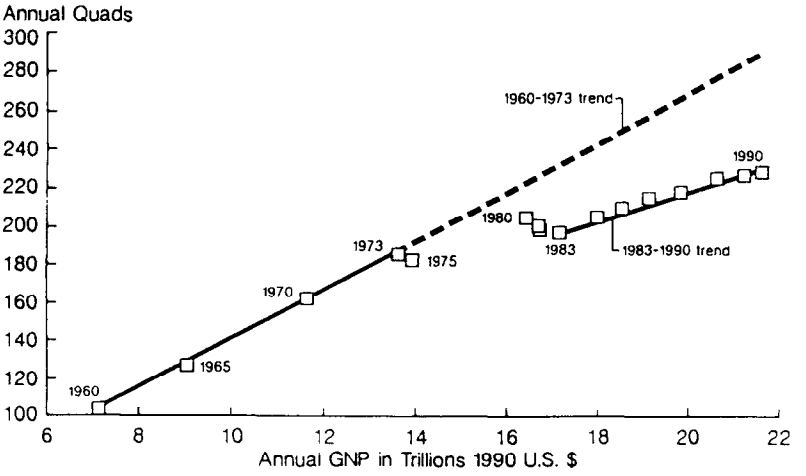

Fig. 3. World annual direct energy use in quads vs GNP (1960-1990) for 10,000 Btu/kWh.

A key parameter is the global population. Figure 4 shows our chosen

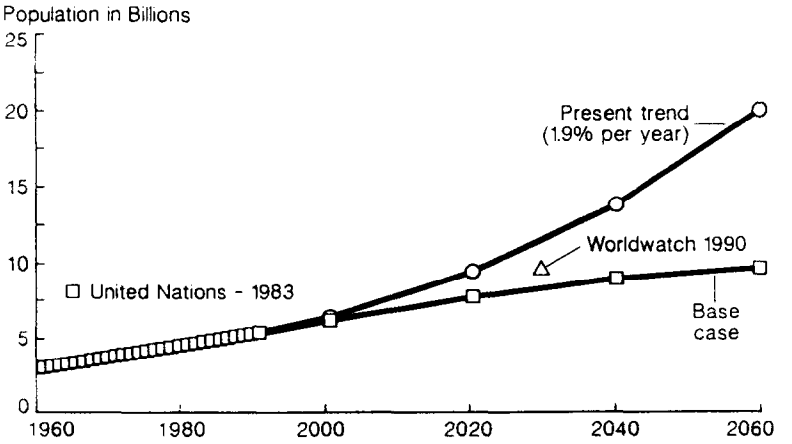

Fig. 4. World population in billions for the period 1960 to 2060.

projection based on a combination of World Bank and United Nations estimates. Figure 5 expands this to illustrate that the LDCs will be the likely source of most of the growth, even though the rate of growth may be decreasing everywhere. This is a key premise for projecting the future. We believe this is a conservative population estimate.

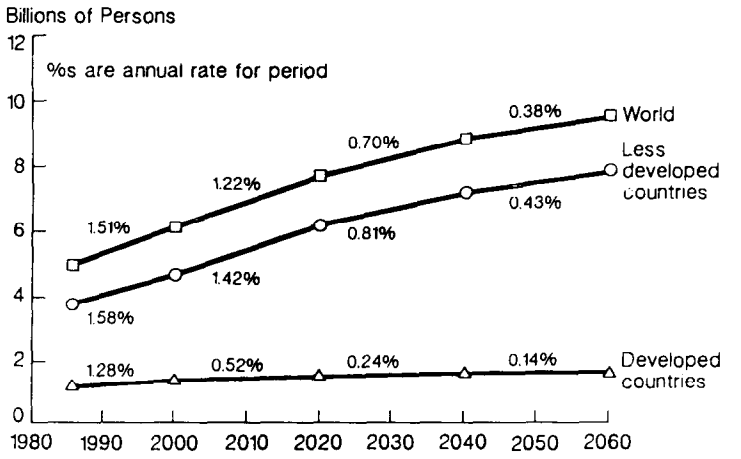

Fig. 5. World and regional populations in billions for the period 1986-2060.

Based on historical world per capita energy and electricity data[1, 2] we have arrived at long-term trend assumptions for per capita energy use in the absence of increased conservation efforts. Due to the variability in the data during the last several decades, estimating these trends involves judgment. Our trend projection for future world energy growth per capita is 1.1% per year, and for electricity 1.75% per year. These per capita growth rates combined with the population projections give our base case.

This base case must be modified by anticipated improvements in the efficiency of energy use. The potential size of such improvements is a matter of much uncertainty. In 1978 the Electric Power Research Institute published an extensive study of the potential for conservation in the United States in electricity and total energy use. In Fig. 6 for energy and Fig. 7 for electricity we have

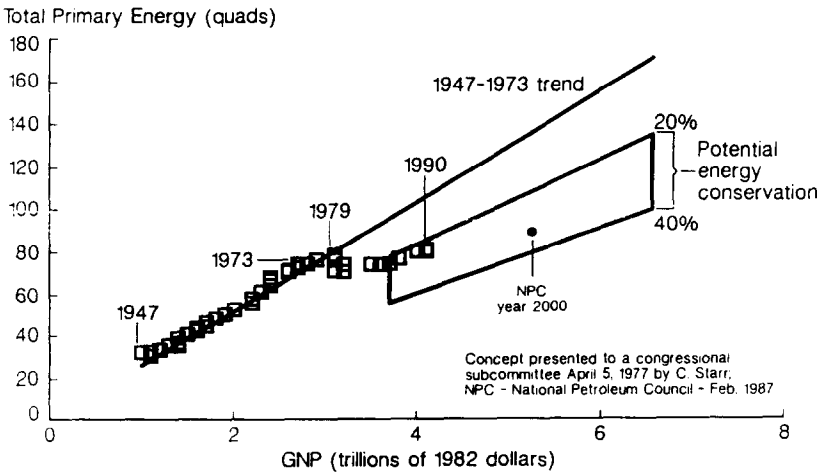
Total Primary Energy (quads)
1947-1973 trend
20%
Potential energy conservation
40%
1990
1979
1973
1947
NPC year 2000
Concept presented to a congressional subcommittee April 5, 1977 by C. Starr; NPC - National Petroleum Council - Feb. 1987
0 20 40 60 80 100 120 140 160 180
0 2 4 6 8
GNP (trillions of 1982 dollars)

Fig. 6. Effect of energy conservation on the total primary energy (quads) vs GNP.

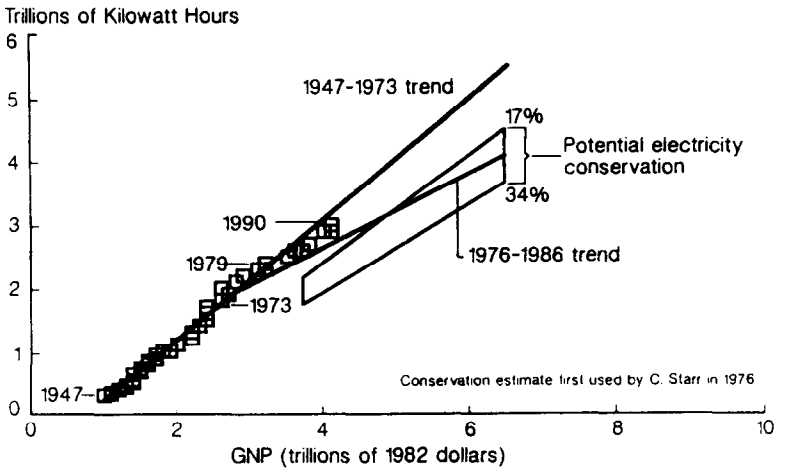

Fig. 7. Effect of conservation on the electricity-GNP relationship in the U.S.

illustrated by the schematic trapezoids the likely potential for such reductions. These figures also show the relationship of actual use to economic growth since the early 1950s. There has been some conservation since the first oil embargo in 1973 but it has been less than might have been expected. Nevertheless, using the potential for conservation shown by the two trapezoids we have made assumptions as to how much conservation the world might achieve by 2060. *As an optimistic projection, we have assumed the eventual achievement worldwide of a* ***Full Conservation*** *Case, in which the use of non-electric energy is reduced to 1/2 of the base Case and the electricity use is reduced to 2/3 of the base case.* We believe this Full Conservation case is probably the best that technology will be able to do without impairing economic growth.

Of major importance is the special role of electrification in achieving economic growth and improvements in resource use efficiency. Schurr et al[3] described the electrification of industry as an "Agent of Technological Progress." The cumulative evidence for this is shown in Fig. 8. Since the 1910-1920 era, the U.S. ratio of energy input per unit of economic output has dropped steadily as the fraction of electricity in the mix has increased. This correlation of electricity use

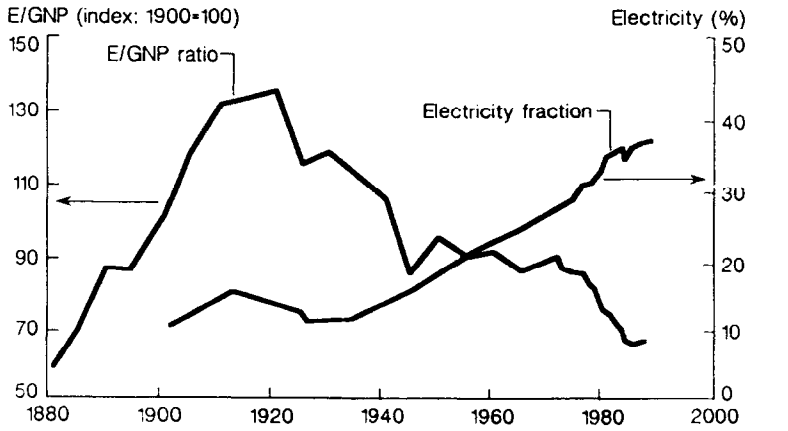

Fig. 8. U.S. energy/GNP ratio and electricity fraction (1880-1988).

with economic growth is characteristic of all countries. Similarly, Fig. 9 shows the global population groups in relation to their electricity use and economic status. *It is now generally accepted that electrification is an economic imperative for all countries.* Electricity use is therefore the basis for our projections of economic growth. Economic growth is the last major parameter for completing the projection. We choose to use the historical electricity/economy relationship so that the economic growth rate is a dependent outcome determined by the electricity assumptions. It is interesting that this process leads to a global economic growth rate of 2.3% per year, certainly a reasonable expectation, and probably a minimum political target.

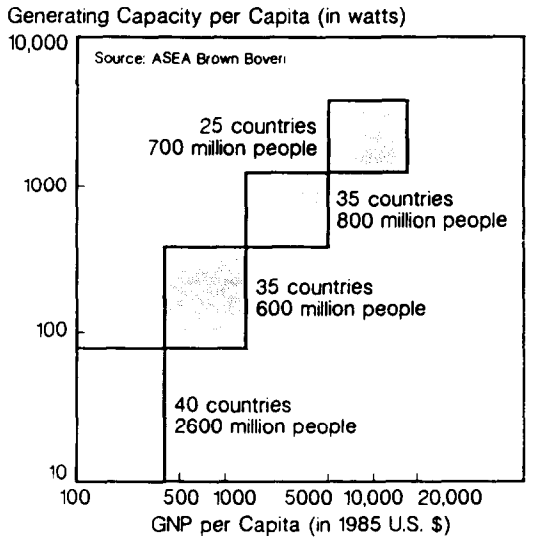

Fig. 9. Relation of prosperity to electric energy consumption.

Let us now discuss the results of this projection. We have taken the year 2060 as our representative target for analysis because of the availability of World Energy Council fuel-resource studies to that date. For various reasons, we assumed that the global fossil fuel mix of coal, oil, and gas will not change substantially. We have also assumed that by 2060 the renewable energy sources such as solar, wind, geothermal, and biomass will have become commercially successful and be utilized at their maximum reasonable contribution shown in Tables 1 and 2. The wind and geothermal contributions were considered too small

Table 1. Assumptions to reach maximum solar electricity in 2060.

Typical electrical load patterns consist of base, intermediate, and peak loads.
Assume solar supplies peak with roughly 1/3 of available capacity.
Assume a high diurnal availability of 29%.
Then, the solar electricity output is 12.7% of the total, and the global contribution is 0.127 x 47000 Twhr = 6000 Twhr.

Table 2. Estimates of dry-mass yield per acre per year for large-scale commercial production, based on empirical data. It is assumed that 5.45% of land area has biomass potential.

Yields and Energy Content S	1990	2060
Dry mass yield (tons per managed acre per year)	6.0	12.0
Per ton energy content (gigajoules)	16.4	16.4
Energy per acre per year (gigajoules)	98.0	197.0
United States estimate 124 million acres converted at 35% efficiency (trillion kWh)	1.20	2.40
Global estimate 575 million acres converted at 35% efficiency (trillion kWh)	5.50	11.0

for inclusion in this rough analysis. Without very low cost energy storage, not now available, we do not believe solar energy will contribute economically more because of the limitations of the daily solar cycle and dependence on the weather. The biomass contribution is more uncertain because of its marginal economics and the competition with food for arable land. Biomass might flourish primarily in the wet tropical countries. We believe our estimate is reasonably optimistic for an economically viable global contribution.

Table 3. Year 2060 energy-and electricity-supplier for past trends and the full conservation case; the primary energy inputs are given in quads.

Scenario	Non-Electric	Electric	Total	% Electric
1986 Base Case	216	105	321	33
Trend Case 2060	773	635	1408	45
Full conservation Case 2060	387	423	810	52

SYNTHESIS

We can now assemble the various projections to provide a composite picture for the year 2060 both for total energy and for electricity. This is summarized in Fig. 10. Without conservation, the base case for 2060 projects a

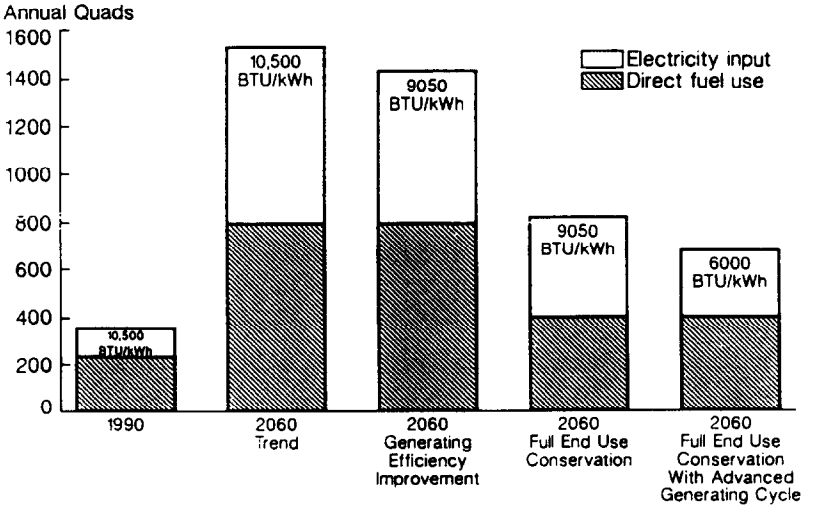

Fig. 10. World year 2060 energy supply.

global energy demand of 1408 quads, as compared to 321 for 1986, an increase of 4.4 times. Assuming a successful full conservation program in all countries, we find that the projected global energy demand is 810 quads, about 2.5 times as large as it was in 1986. Of this, solar energy and biomass at their maximum represent about 19%. Such renewables as wind and geothermal energy are likely to make small contributions to the total.

The projected equivalent fuel input for electricity is 635 quads for the base case and 423 quads with full conservation, respectively, about 6.0 and 4.0 times the present 105 quads. With full conservation, in 2060 the input of equivalent primary fuel for electricity generation is about 52% of the total, and of this, the maximum solar and biomass represents 36%. This is a sizable percentage, and also very large physically, equal to about half of today's total world energy production. These estimates of the solar and biomass potential appear to us very optimistic targets, although feasible in principle.

Table 4. For the world, the population is the weighted average for the LDCs and the DCs.

		Year 2060		
	Actual 1986	Trend	Full Conservation	Zero per Capita Growth
Electricity (kWh/capita)				
LDCs	500	3,590	2,390	500
DCs	6,850	24,730	16,480	6,850
World*	2,010	7,240	4,830	1,600
Total kWh (trillions)				
LDCs	2	29	19	4
DCs	8	41	28	12
World*	10	70	47	16

It appears that by 2060 the LDCs will be using about 44% of the world's energy, as compared with 24% today. As shown in Table 4, the LDCs will then be using about 41% of the world's electrical kilowatt-hours, as compared to 19% today. It is apparent that the future energy strategies of the LDCs will have a major influence on the total world scene. Of course, our projections assume reasonable economic growths for these countries which may not occur. Conversely, we consider a coercive energy constraint which might prevent their economic growth as ethically unacceptable and unenforceable.

We are then left with the question as to how this energy and electricity will be supplied in 2060, and what influence this may have on the global climate. Table 5 shows some of the likely electricity scenarios. As shown in Table 6, if we maintained today's mix of energy sources, fossil fuel would supply 97% of the energy. With our full conservation scenario, fossil fuel plus hydro plus nuclear needs to supply about 81% of the total. The world hydro resources are about 4 times greater than used today, but we have assumed these will not be utilized for ecological and environmental reasons. Nuclear power expansion is open-ended, and we have looked at two feasible cases, 9x and 13x present levels. As shown in Table 6, all these speculations result in substantial increases in the annual global carbon emissions.

Table 5.

Full conservation case: • Limited fossil and hydro
• Maximum solar and biomass

	(1000 TWhr)				
			Maximum		
Year	Total Electricity	Fossil and Hydro	Solar	Biomass	Nuclear
1986	10.0	8.4	--	--	1.6
2060					
	• Fossil fuel and hydro at 1986 level				
	47	8	6	11	22
	• Fossil fuel and hydro = nuclear				
	47	15	6	11	15

Table 6. Year 2060 energy and CO_2 range.

	Base Case	Full Conservation Case With Max Solar & Biomass	
Energy Sources	1986 Nuclear	Low Nuclear	High Nuclear
Fossil fuels	1,365	494	431
Hydro	28	28	28
Nuclear	15	135	198
Solar	0	54	54
Biomass	0	99	99
Total Supply	1,408	810	810
Gigatons Carbon	27.3	9.9	8.6
Ratio C to 1986	5.0	1.8	1.6

In constructing this projection, we have assumed modest population and economic growth and optimistic estimates of conservation, solar, and biomass contributions. The composite supply spectrum for the time period to 2060 is shown in Fig. 11. It is interesting to consider the consequences of a change in the world's economic growth rate on the time required to arrive at our nominal year

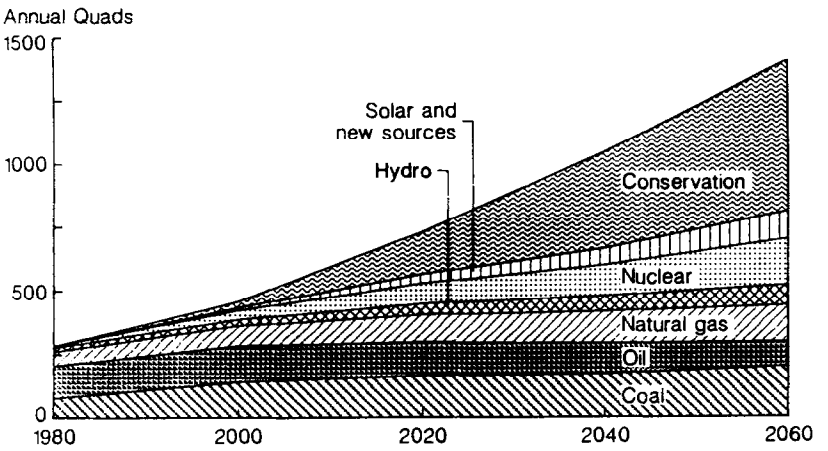

Fig. 11. Conservation case by energy type.

2060 status, as shown in Fig. 12. For example, if the average growth rate is reduced from the 2.3% reference case to 1.5%, it would take 100 years to reach the same situation. We consider the economic growth rate as the most uncertain parameter in such a long-range projection. Conversely, we also expect only partial achievement of full conservation targets and the growth of renewables. *We therefore expect at least a doubling of annual carbon emissions globally by the mid-21st century, even with a strong international movement to implement conservation and renewables.* An increase from the observed 1% per year growth in global CO_2 to 2%/year reduces the doubling time from 70 to 35 years.

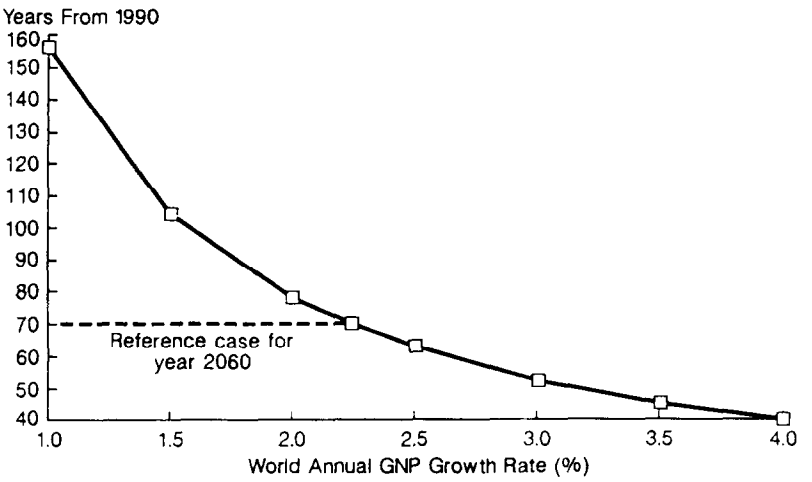

Fig. 12. Years to full conservation case vs GNP (%).

The climate significance of such an increase in annual carbon emissions may eventually prove to be very serious, but our present understanding of the interactive dynamics of biosphere processes is inadequate to predict the consequences. A decade or more of intensive scientific study of the biosphere and its climate will be needed before we can project events with enough confidence to guide policy. We need to establish a comprehensive global monitoring system to track biospheric trends on a continuous bases.

However, we need not wait. It is certainly prudent to initiate reasonable steps to reduce carbon emissions. An obvious step is the promotion of the efficient use of fossil fuels by appropriate incentives, a topic that is widely discussed. A less obvious step is the development of innovative processes and systems that result in reduced energy demand. The history of production in the U.S. shows that the electrification of industrial systems reduced the energy input per unit of economic output by a factor of 2. Much remains to be done, as for example in the electrification of transportation. The electric automobile for urban use may become a commonplace in a few decades, and if electricity came from non-fossil sources, carbon emission reduction could be substantial. Much has been written about the reduction of demand by the energy user in buildings and appliances. These concepts are the basis for our optimistic conservation projections.

A further obvious step is the continued encouragement of electricity supply from non-fossil sources -- solar, wind, geothermal, hydro, and nuclear-- to achieve economic acceptance as viable alternatives. The intermittent sources (solar energy and wind) require low cost energy storage to contribute beyond the roughly 5-15% limitation of electricity networks. Hydro faces environmental constraints. Nuclear is technically cost competitive now, but carries the burden of public fears and regulatory strictures. None of these constraints are insuperable, and improved technology may open the way for expansion of these sources.

Given that such technical opportunities exist for the industrial countries, we face the broader consequences of the economic growth of the less developed regions. Their population growth should slow down as their economic welfare increases, but their energy needs must be met first if this is to occur. Our objective should be to ensure that this is done most efficiently. This task of technology transfer is socially and culturally monumental. In the LDCs, immediate national capital resource demands may overwhelm long term global concerns. Further, the argument can be made that even energy-inefficient economic growth in the LDCs may make them more resilient to a future climate change. Perhaps it is better to have an inefficiently air-conditioned hospital than no air-conditioning at all. As a technologist, I believe that with time we should be able to meet both cost and efficiency objectives in these LDCs, but it will take a major effort to do so. As a preliminary step, I suggest that the industrial countries establish an "Energy Corps" made up of volunteers to work with the LDCs on the implementation of their energy systems and uses.

Another technical facet of the climate issue is the search for carbon sequestering, i.e. pulling carbon out of the atmosphere. The idea of recycling carbon back to its original state underground is manifestly implausible. However, carbon dioxide may be temporarily stored in biomass. If the biomass is used as fuel, only a residual sequestering takes place in the root structure left in the soil. If used for furniture or building construction, sequestering might last several decades. Other schemes for capturing CO_2 in flue gases and storing it in various cavities or in the deep ocean are theoretically feasible but studies show them to be extremely costly and to increase primary energy demand substantially. Imaginative thinking continues.

So where does this leave us? These are my opinions.

1. *During this coming century, we should expect at least a doubling of our annual carbon emissions, no matter how well we do on conservation by efficiency improvements or by expanding solar and biomass.* The increase will be greater if we accomplish less in these areas.

2. *A global program for the use of efficient energy systems, and for the stimulation of non-fossil sources should be organized now.* Of these, only nuclear power is a currently proven major energy source capable of major expansion. Public fears not withstanding, a strong analytical case can be made that nuclear power systems are safer than the fossil fuel systems. The international management of a global nuclear power fuel cycle should be studied now in anticipation of such expansion.

3. *We should recognize that economic growth must not be sacrificed in order to reduce carbon emissions.* In a world in which the greatest social pollution arises from poverty, starvation, misery and ill-health, the development of the economic resources to mitigate these social pollutants must have the top priority. The highly visible affluent minority that can comfortably make sacrifices is a minor economic sector compared to the economic needs of the impoverished majority.

4. *Totally unrealistic is the on-going international political exercise to negotiate a mandated reduction of global carbon emissions of 20% and to maintain this reduced level for the future.* Only in a fictional world of dictatorial population limitation might such an objective be feasible. In our real world, such an agreement would be socially destructive if seriously implemented. It would devastate the economic growth of the less developed countries. If not seriously implemented, as is likely, it would become a permanent "cause celebre" and a political weapon for those parochial self-interests that are rooted in their antipathy to technology and the industrialization of society.

5. *The international political momentum for immediate action has been stimulated by public fear-mongering based on hypothetical scenarios of drastic climate change.* The sole scientific evidence to-date is the measured continuous increase in atmospheric carbon dioxide. All else is speculation based on several simplified models that only crudely represent the biosphere, and that disagree with each other, particularly on the important question of rainfall distribution. We have a welter of uncertainty about the character of the potential climate changes. Competent scientists are avidly seeking a better understanding of the complex dynamics of the biosphere, but much needs to be done before reasonably reliable forecasts of climate changes can be made. Unfortunately, in the meanwhile, public fear is being promoted by highly visible self-interest organizations with no accountability for eventual outcomes.

6. *Adaptation to climate change appears feasible with little economic strain if it occurs slowly, as appears likely.* A recent study by federal meteorologists suggests that it may take 20-40 years to detect from weather records that change is actually occurring. Apocalyptic temperature increases are not foreseen. Temperature differences between our southern and northern cities are larger than the projected increases of 1.5-4.5 C (3-8 F). The average annual temperature difference between Los Angeles and San Francisco is 6 F, about the same as the model projections, and

between Chicago and New Orleans it is 19 F, three times the model projections. If my grandchildren eventually need to adapt to such temperature shifts, I have confidence that they will easily do so.

7. *We should recognize that a climate change may be globally beneficial rather than harmful.* While it is likely that any climate change will slowly redistribute rainfall, floods, and drought, the present uncertainty provides an equal probability that many parts of the world will benefit by such change. However, such an optimistic speculation does not preclude the current need for more climate research to improve our understanding, and for the stimulation of efficiency and of non-fossil sources. These buy us time to reduce our ignorance and fear.

If my view recalls that of Dr. Pangloss, the optimistic tutor in Voltaire's Candide who believed that all is for the best in this best of possible worlds, it is perhaps because I have faith in science and technology, and in the good judgment of professionals like you. My deep concern relates to the on-rushing political momentum toward immediate drastic action. We suffer from the international fear-mongering created by the parochial views of those who want to save the world by stopping it.

In our democracy, we must all participate in the political debate as best we can so that eventually the public's common sense will be given an opportunity to prevail.

I believe it important that all of us expand our professional interests to include participation, as best we can, in the current public and political discussions on our national energy policy and the issues that are basic to its formulation. It is not our consensus that the public needs, rather it is our professional perception of the realities we must deal with. To paraphrase a historical quote, "Energy policy is much too serious to be left to the politicians".

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